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Digital Simulation of VFT Applications between Power System Networks

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***Abstract*- Recently, a new technology known as variable frequency transformer (VFT) has been developed for transmission interconnections. It is used as a flexible asynchronous ac link to transfer power between power system networks. Basically, it is a rotary transformer whose torque is controlled by dc drive in order to control the power transfer. This paper discusses various applications where VFT technology can be used as a tie between power system networks. Its use to facilitate connections between synchronous and asynchronous systems is discussed along with its general operational characteristics in these applications. For this, a digital simulation model of VFT is presented. A digital simulation model of VFT and its control system are developed with MATLAB Simulink and a series of studies on power transfer through power system networks are carried out with this model. Moreover, the response characteristics of power transfer under various torque conditions are discussed. Further voltage, current, torque and power transfer plots are also obtained. Thus, the VFT concept and its applications are verified by simulation results**.

***Index Terms*— Variable Frequency Transformer (VFT), Transmission interconnection, Flexible asynchronous ac link, Power transfer, Power System networks, MATLAB Simulink.**

I. INTRODUCTION

Variable frequency transformer (VFT) is a controllable, bidirectional transmission device that can transfer power in-between asynchronous power system networks [1-8]. The construction of VFT is similar to that of conventional asynchronous machines, where the two separate electrical networks are connected to the stator winding and the rotor winding, respectively. One power system is connected with the rotor side of the VFT and another power system is connected with the stator side of the VFT. The electrical power is exchanged between the two networks by magnetic coupling through the air gap of the VFT and both are electrically isolated [1].

The VFT is essentially a continuously adjustable phase shifting transformer that can be operated at an adjustable phase angle. The VFT consists of following core components: a rotary transformer for power exchange, a drive motor to control the movement or speed of the rotor and to control the transfer of power. A drive motor is used to apply torque to the rotor of the rotary transformer and adjust the position of the rotor relative to the stator, thereby controlling the magnitude and direction of the power transmission through the VFT [2]. The world's first VFT, was manufactured by GE, installed and commissioned in Hydro-Quebec's Langlois substation, where it is used to exchange power up to 100 MW between the asynchronous power grids of Quebec (Canada) and New York (USA) [3].

A stable real power exchange between the two asynchronous systems is possible by controlling the torque

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applied to the rotor, which is controlled externally by the drive motor [4]. When the power systems are in synchronism, the rotor of VFT remains in the position in which the stator and rotor voltage are in phase with the associated systems. In order to transfer power from one system to other, the rotor of the VFT is rotated. If torque applied is in one direction, then power transmission takes place from the stator winding to the rotor winding. If torque is applied in the opposite direction, then power transmission takes place from the rotor winding to the stator winding. The power transmission is proportional to the magnitude and direction of the torque applied. The drive motor is designed to continuously produce torque even at zero speed (standstill). When the two power systems are no longer in synchronism, the rotor of the VFT will rotate continuously and the rotational speed will be proportional to the difference in frequency between the two power systems (grids). During this operation the power transmission or flow is maintained. The VFT is designed to continuously regulate power transmission even with drifting frequencies on both grids. Regardless of power transmission, the rotor inherently orients itself to follow the phase angle difference imposed by the two asynchronous systems [5-8].

II. VFT MODELING

In the modeling, the VFT is modeled as a doubly-fed wound rotor induction machine (WRIM), the three phase windings are provided on both stator side and rotor side. The two power systems (#1 and #2) are connected through the VFT as shown in Fig. 1. The power system#1 is connected to the stator side of the VFT, energized by voltage, V_S with phase angle, θ_S. The power system#2 is connected to the rotor side of the VFT, energized by voltage, V_r with phase angle, θ_r. A drive motor is mechanically coupled to the rotor of WRIM. A drive motor and control system are used to apply torque, T_D to the rotor of the WRIM which adjusts the position of the rotor relative to the stator, thereby controlling the direction and magnitude of the power transmission through the VFT [7-8].

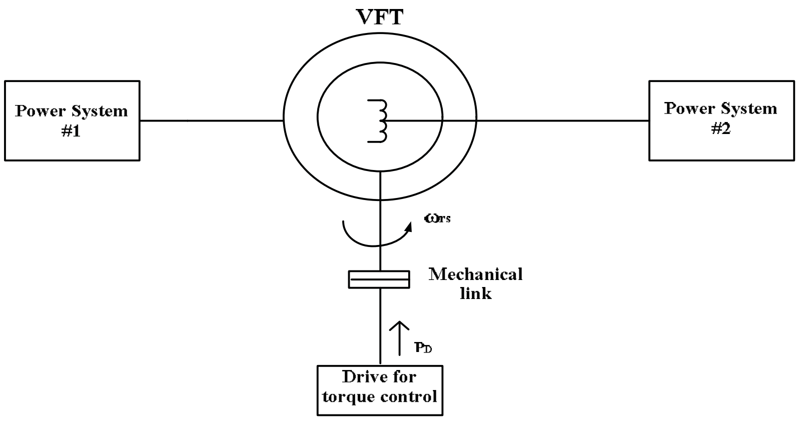


Figure 1. The VFT model representation

The power transfer direction shows the power transmission from power system#1 to power system#2 through VFT. In fact, the direction of power transfer could be from power system#1 to power system#2 or vice-versa depending on the operating conditions. If torque is applied in one direction then power transfer takes place from power system #1 to power system#2. If torque is applied in opposite direction then power transfer reverses. Here, in the power transfer process, only real power transfer is being discussed.

III. MATLAB SIMULATION MODEL OF VFT

For simulation in MATLAB, VFT is represented as a wound rotor induction machine (WRIM). The WRIM is doubly-fed, 3 phase, 4kW, 400V, 50 Hz and is simulated with the asynchronous machine SI units in MATLAB Simulink [7-8]. The power system#1 and power system#2 are simulated with three phase voltage sources as shown in Fig. 2. The three phase voltage source 1 is connected to the stator side of WRIM and the three phase voltage source 2 is connected to rotor side of WRIM. The drive motor is simulated with constant block which gives constant torque. The torque is applied to WRIM as mechanical torque T_m. To simulate various power transfer functions, other blocks are also used.

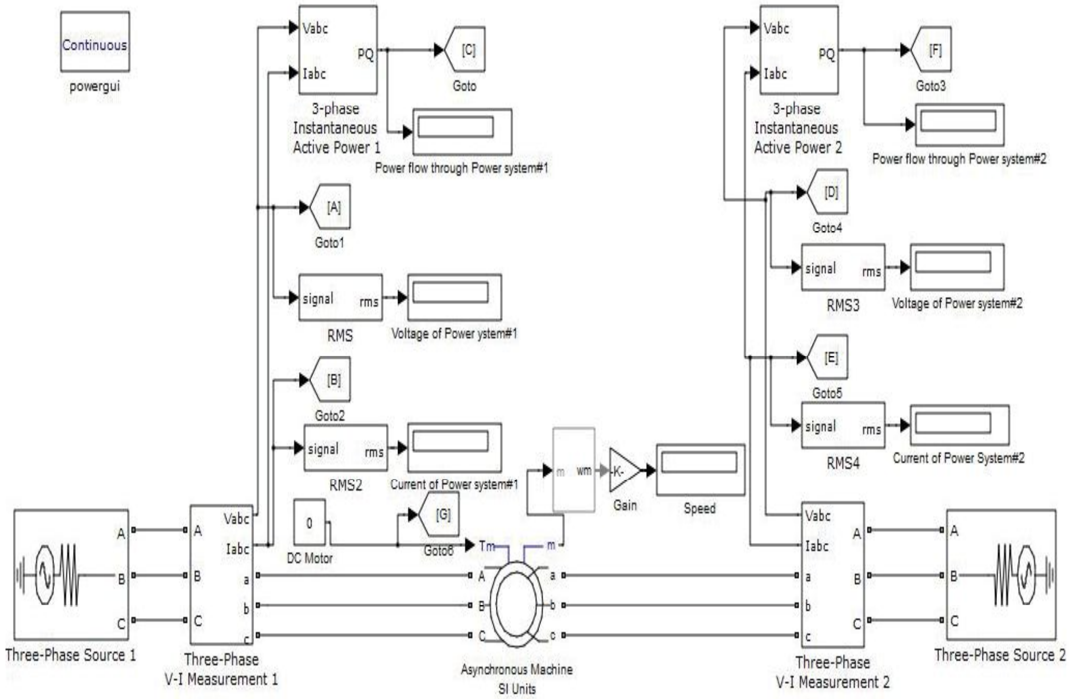


Figure 2. MATLAB Simulation model for VFT applications between power systems networks

IV. Simulation of VFT System Applications

A. Power Flow Control within Synchronous Power Systems

The most basic application of a VFT system is for power flow control between buses embedded within a synchronous, singly dispatched power system (Fig. 3). In this application the VFT can perform the same function as a conventional phase angle regulating (PAR) transformer, but with more precision and controllability [4].

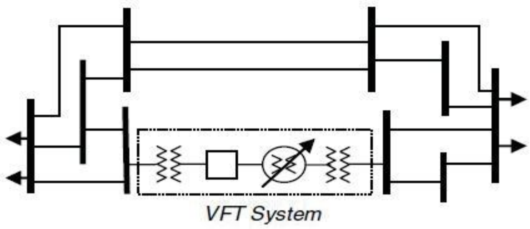


Figure 3. VFT system embedded within a power system network [4].

For the analysis of power flow control within synchronous power systems in MATLAB Simulink, the power system#1 and power system#2 are same power system and kept at 400V (L-L) and 50 Hz. Then this simulated model, as shown in Fig. 2, is used to analyze electric power system using VFT. Under different torque conditions, the power transfer through power system#1 and power system#2 is simulated. The simulated waveforms of stator voltage, rotor voltage, stator current, rotor current, speed and torque are shown in Figs. 5 – 15.

Power transfer from Power system#1 to Power system#2:- It is evident from the simulated results that under different external torque condition, the power transfer through the power system#1 and power system#2 is not zero. The magnitude and frequency of voltage are kept same for all operating conditions (Fig. 4) and the power transfer through power sytem#1 and power system#2 under different torque condition are shown in Figs. 5-10.

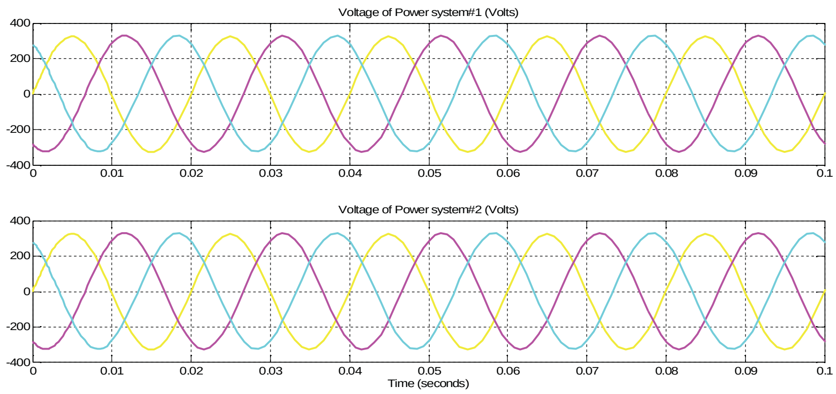


Figure 4. Per phase voltage waveforms of stator and rotor side of VFT.

TABLE I. MATLAB SIMULATION RESULTS FOR WITHIN SYNCHRONOUS POWER SYSTEMS

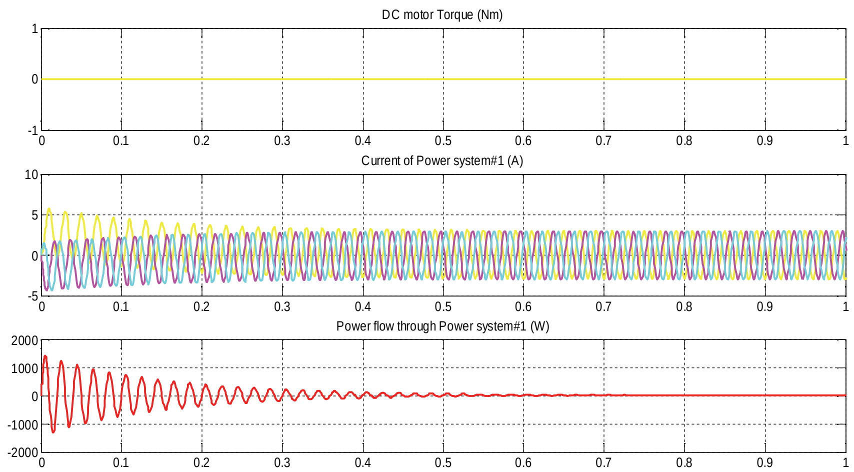
S. No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r(W)
1	0	2.013	18.61	2.013	18.48
2	5	1.465	797	3.388	-733.2
3	10	2.409	1603	4.939	-1458
4	15	3.891	2437	6.546	-2154
5	20	5.506	3299	8.179	-2823
6	25	7.180	4190	9.832	-3463

TABLE II. MATLAB SIMULATION RESULTS FOR WITHIN SYNCHRONOUS POWER SYSTEMS

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r (W)
1	0	2.013	18.61	2.013	18.48
2	-5	3.387	-732.8	1.465	796.9
3	-10	4.937	-1457	2.409	1603
4	-15	6.539	-2153	3.889	2436
5	-20	8.168	-2821	5.503	3297
6	-25	9.826	-3460	7.174	4187

For T_D = 0 Nm, Fig. 5 shows the waveforms

It is clear from table I that under zero torque condition the power transfer through the VFT is zero even though there is power transfer through power system#1 and power system#2 i.e. VFT is taking power from both the power systems. When the torque applied is in one direction, then power transmission takes place from power system#1 to power sustem#2. The negative sign represents the power transfer inside the power system#2.



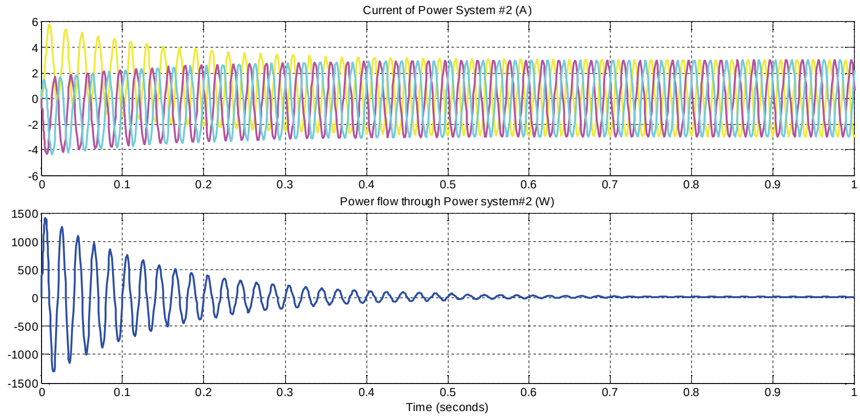


Figure 5. Waveforms showing torque, currents and power transfer

For T_D = 5 Nm, Fig. 6 shows the waveforms.

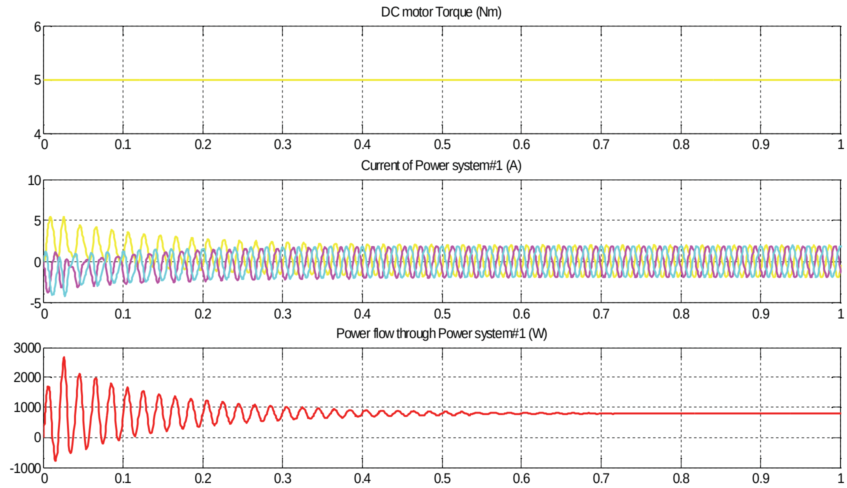
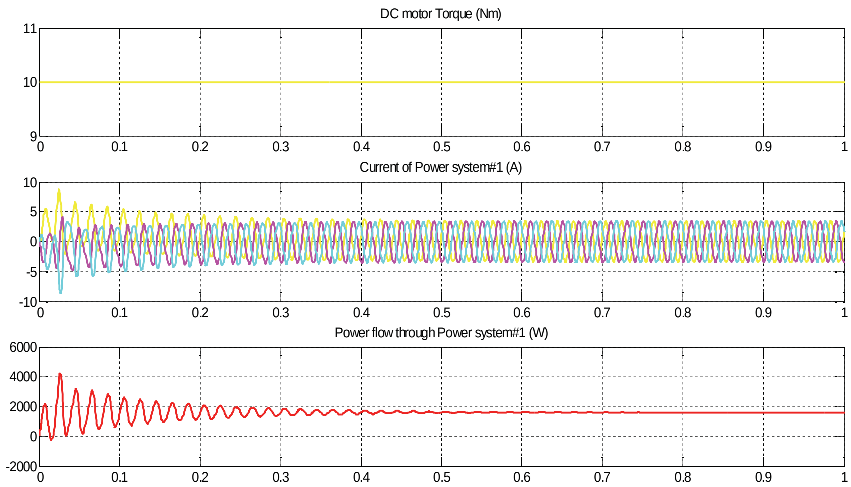


Figure 6. Waveforms showing torque, currents and power transfer

For T_D = 10 Nm, Fig. 7 shows the waveforms



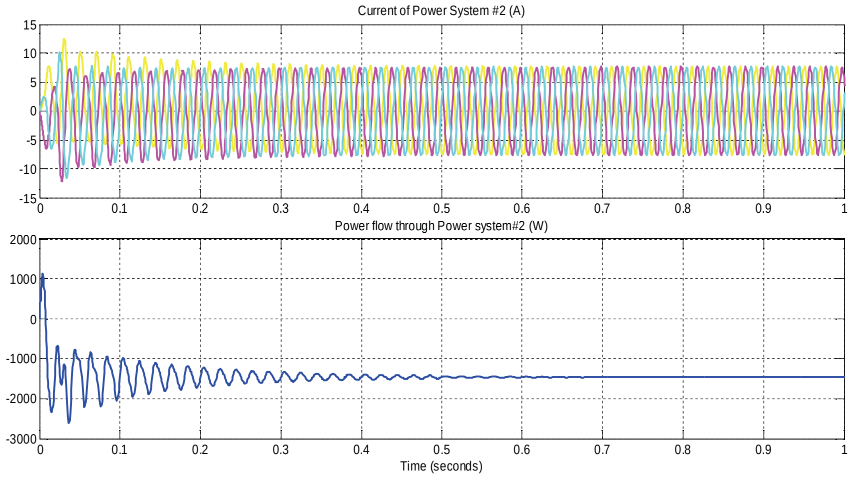


Figure 7. Waveforms showing torque, currents and power transfer

For T_D = 15 Nm, Fig. 8 shows the waveforms.

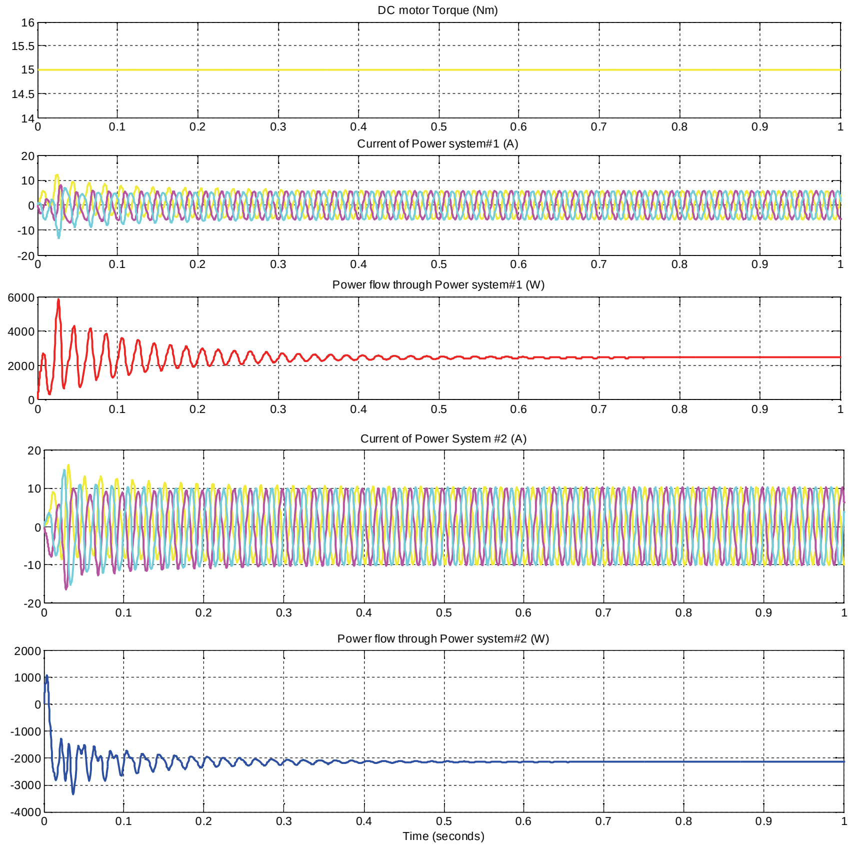


Figure 8. Waveforms showing torque, currents and power transfer

For T_D = 20 Nm, Fig. 9 shows the waveforms

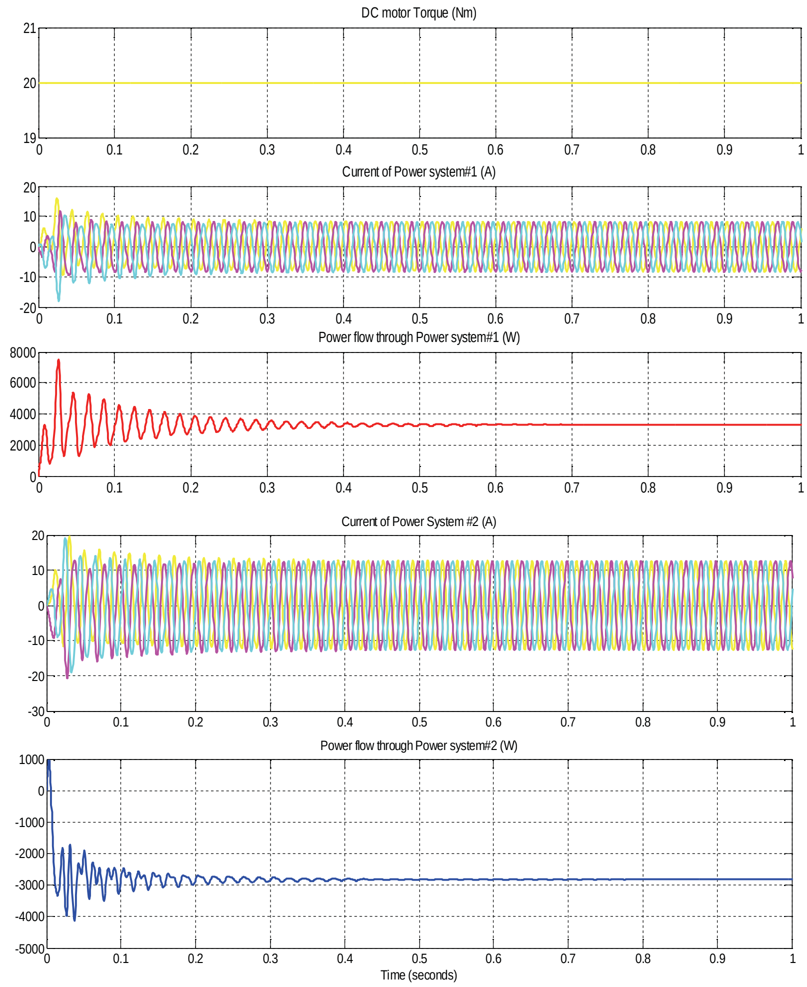
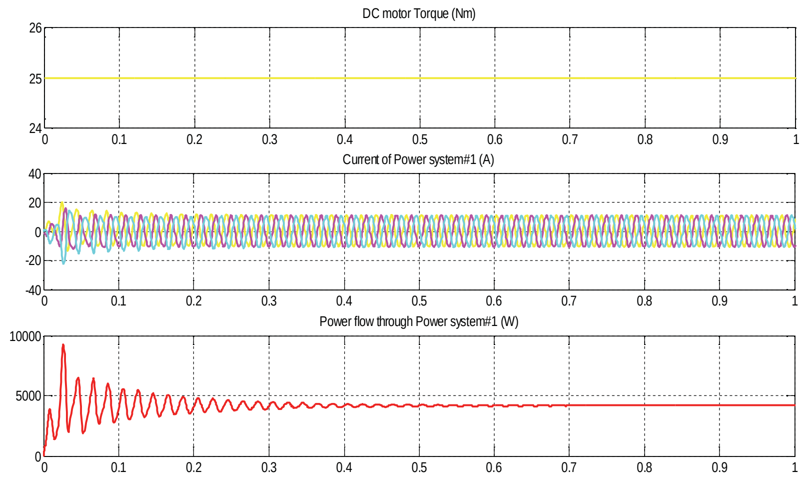


Figure 9. Waveforms showing torque, currents and power transfer

For T_D = 25 Nm, Fig. 10 shows the waveforms.



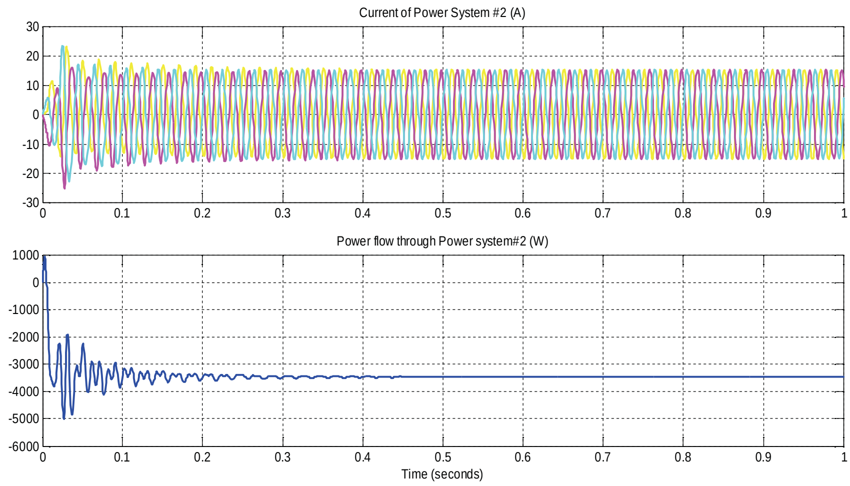


Figure 10. Waveforms showing torque, currents and power transfer

Power transfer from Power system#2 to Power system#1:- When the applied torque is in opposite direction then power transfer direction reverses as shown in Figs. 11-15.

It is clear from table II as the applied torque direction reverses the power transfer direction also reverses i.e. the power transmission takes place from power system#2 to power sustem#1. The negative sign represents the power transfer inside the power system#1.

For T_D = - 5 Nm, Fig. 11 shows the waveforms

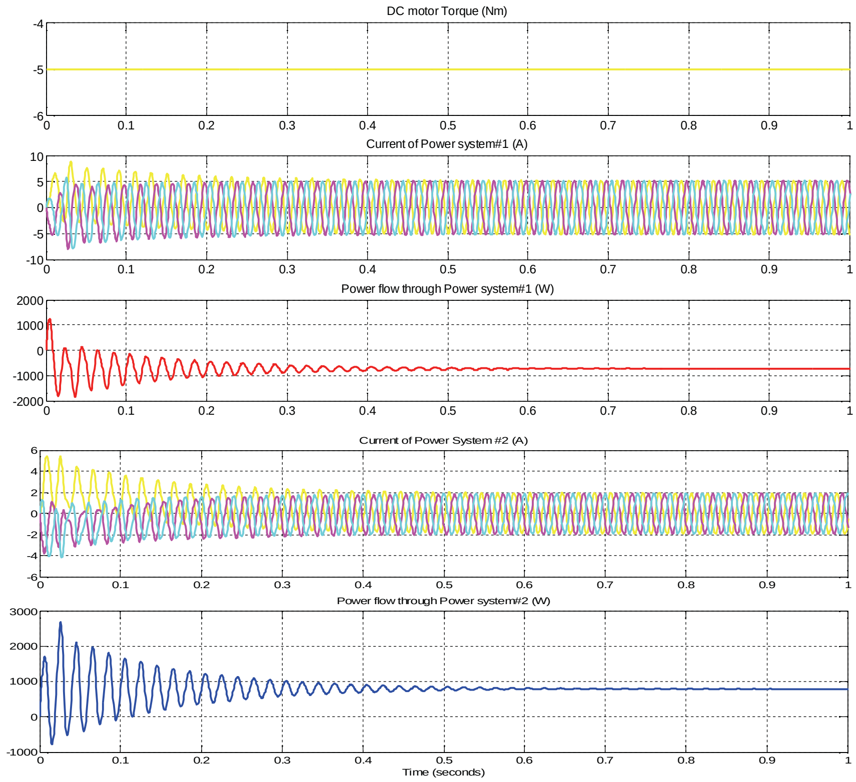


Figure 11. Waveforms showing torque, currents and power transfer

For T_D = - 10 Nm, Fig. 12 shows the waveforms.

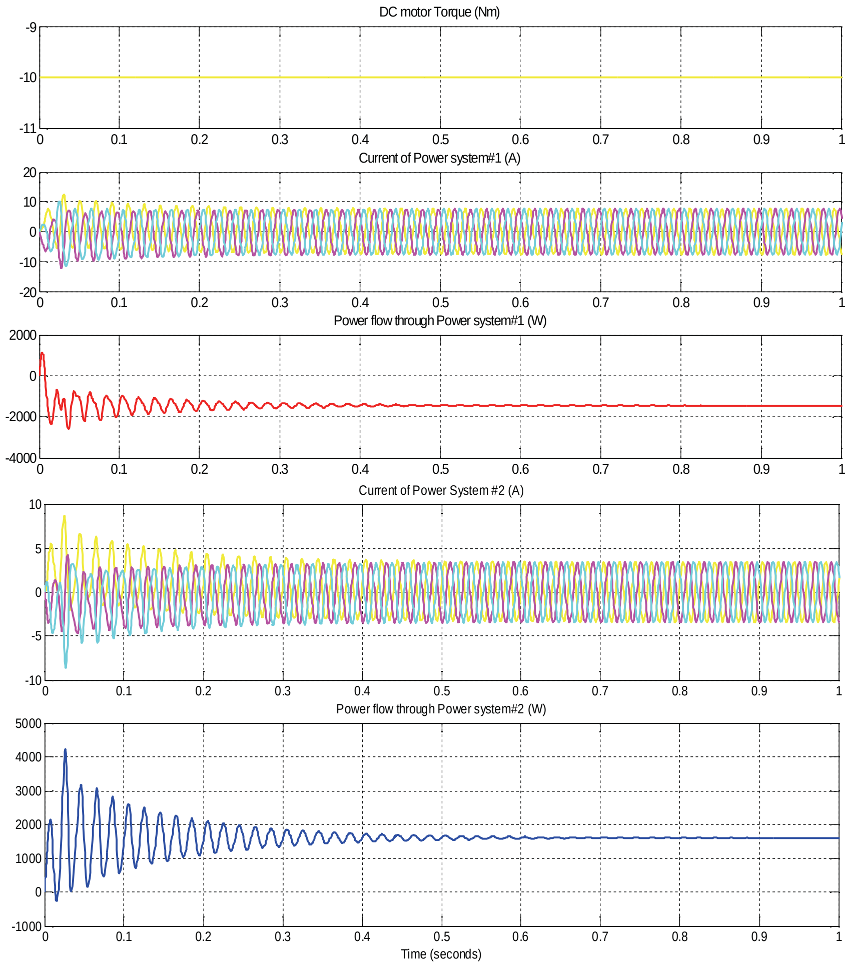
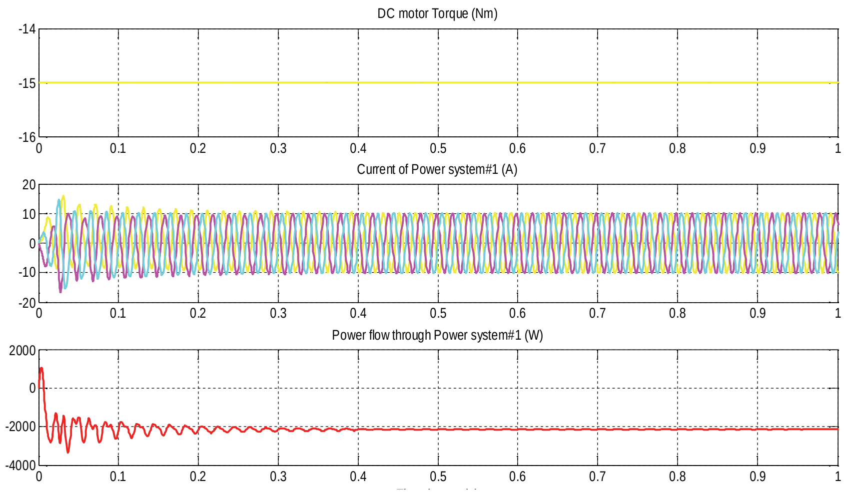


Figure 12. Waveforms showing torque, currents and power transfer

For T_D = - 15 Nm, Fig. 13 shows the waveforms



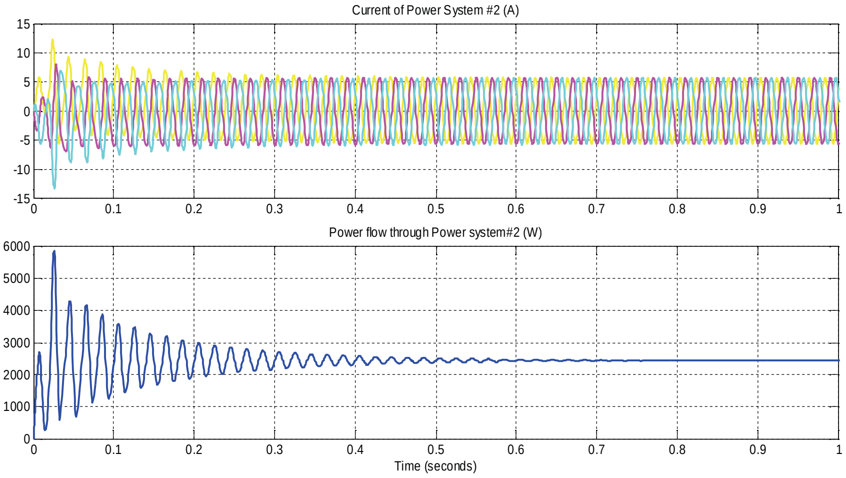


Figure 13. Waveforms showing torque, currents and power transfer

For T_D = - 20 Nm, Fig.14 shows the waveforms

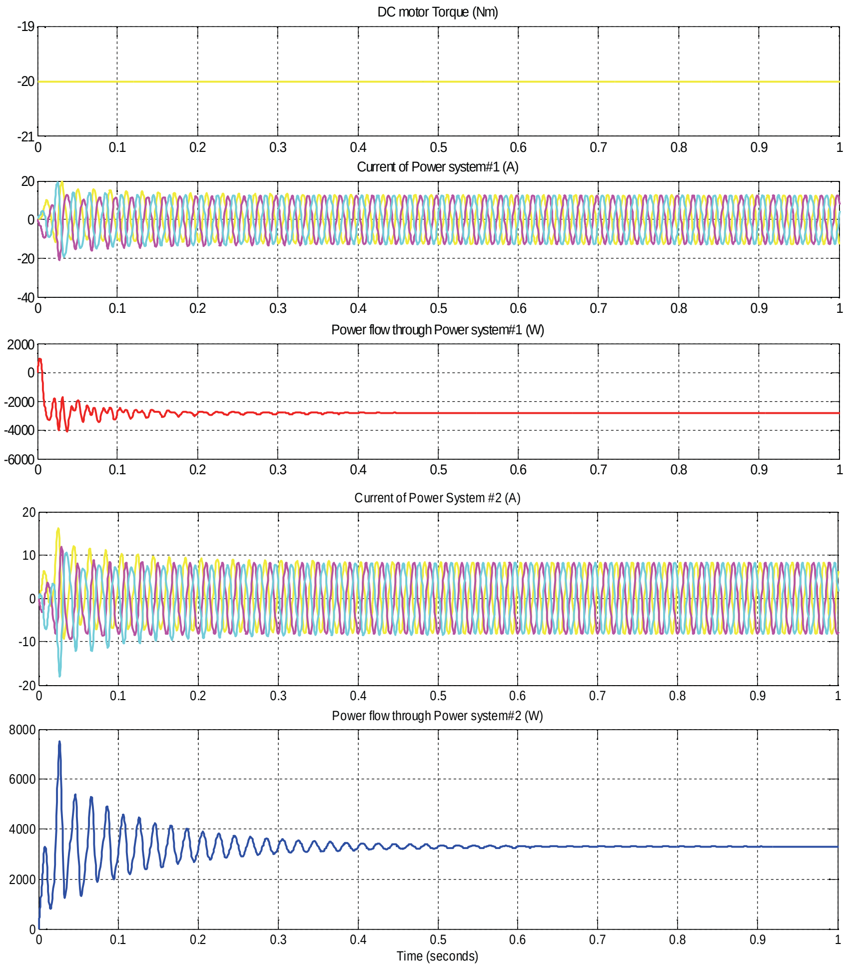


Figure 14. Waveforms showing torque, currents and power transfer

For T_D = - 25 Nm, Fig.15 shows the waveforms.

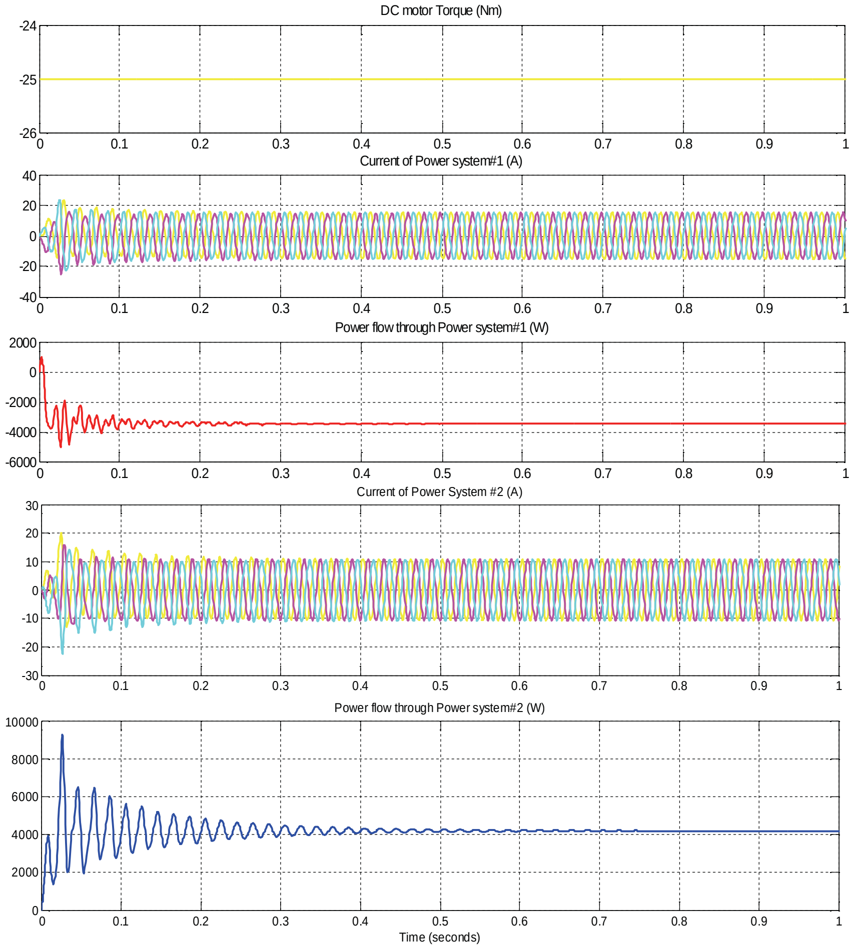


Figure 15. Waveforms showing torque, currents and power transfer

The power transfer through power system#1 and power system#2 with the applied torque achieved is shown in Fig. 16.

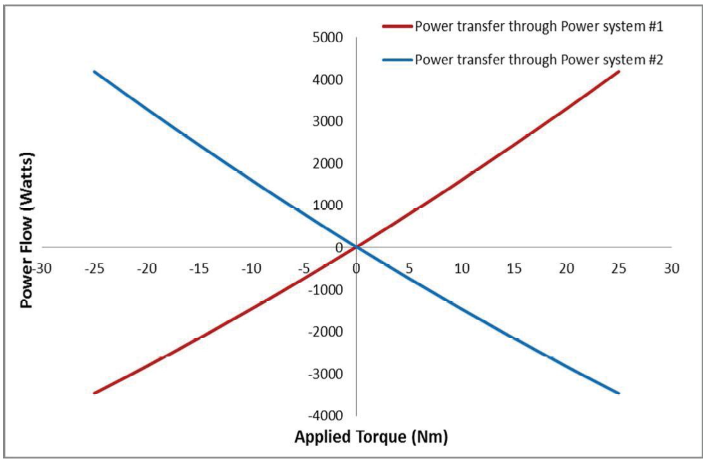


Figure 16. The power transfer within power system with the applied torque.

B. Power Flow Control in-between Synchronous Power Systems

In some cases it may be desirable to regulate flows on existing tie lines between two separately dispatched power systems (i.e. different control areas) as shown in Fig. 17, or to create a regulated tie line where none currently exists. This may be driven by reliability issues such as a need to increase transfer capability across an interface or provide access to reserves, or by power market economics or a desire to access varying sources of generation. For example, creating a path for power to be transacted from a lower cost area to a higher cost area may provide the necessary economic motivation for establishing the new tie, which would also provide inherent reliability benefits.

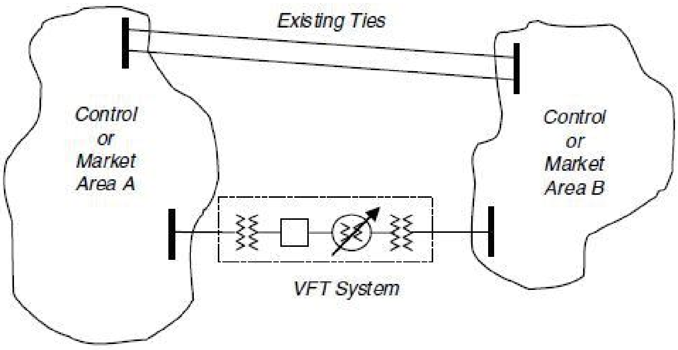


Figure 17. VFT system in-between synchronous power system networks [4].

For the analysis of power flow control in-between synchronous power system networks in MATLAB Simulink, the power system#1 and power system#2 are different power systems having different voltages and same frequencies. The power system#1 are kept at 400V (L-L) and 50 Hz whereas power system#2 is kept at 385V (L-L) and 50 Hz. Then this simulated model, as shown in Fig. 2, is used to analyze electric power system using VFT. Under different torque conditions, the power transfer through power system#1 and power system#2 is simulated.

The magnitude and frequency of voltage are kept same for all operating conditions (Fig. 18).

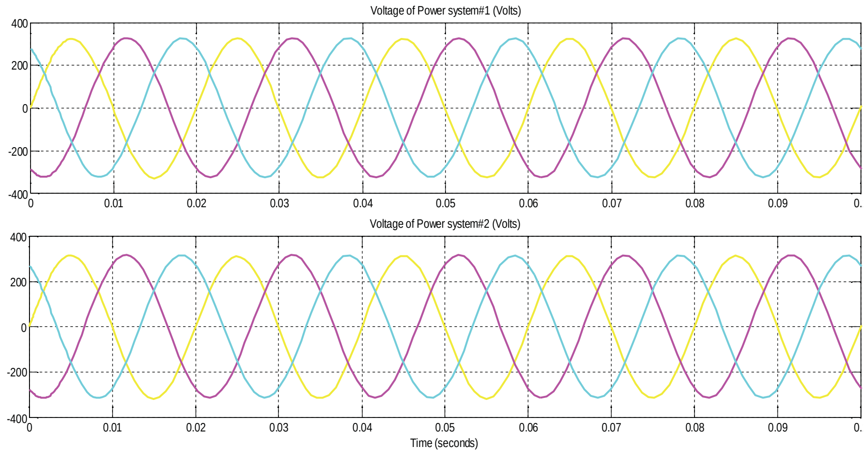


Figure 18. Per phase voltage waveforms of stator and rotor side of VFT.

TABLE III. MATLAB SIMULATION RESULTS FOR IN-BETWEEN SYNCHRONOUS POWER SYSTEMS

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r (W)
1	0	4.193	79.13	0.2316	0.9749
2	5	3.244	830.8	1.661	-777
3	10	2.718	1610	3.540	-1525
4	15	3.649	2418	5.438	-2246
5	20	4.929	3256	7.354	-2940
6	25	6.403	4122	9.295	-3603

It is clear from table III that under zero torque condition the power transfer through the VFT is zero even though there is power transfer through power system#1 and power system#2 i.e. VFT is taking power from both the power systems. When the torque applied is in one direction, then power transmission takes place from power system#1 to power sustem#2. The negative sign represents the power transfer inside the power system#2.

TABLE IV. MATLAB SIMULATION RESULTS FOR IN-BETWEEN SYNCHRONOUS POWER SYSTEMS

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r (W)
1	0	4.193	79.13	0.2316	0.9749
2	-5	5.750	-646.5	2.081	809.3
3	-10	7.503	-1341	3.929	1645
4	-15	9.317	-2007	5.775	2508
5	-20	11.16	-2642	7.620	3403
6	-25	13.03	-3246	9.465	4327

It is clear from table IV as the applied torque direction reverses the power transfer direction also reverses i.e. the power transmission takes place from power system#2 to power sustem#1. The negative sign represents the power transfer inside the power system#1.
The power transfer through power system#1 and power system#2 with the applied torque achieved is shown in Fig. 19.

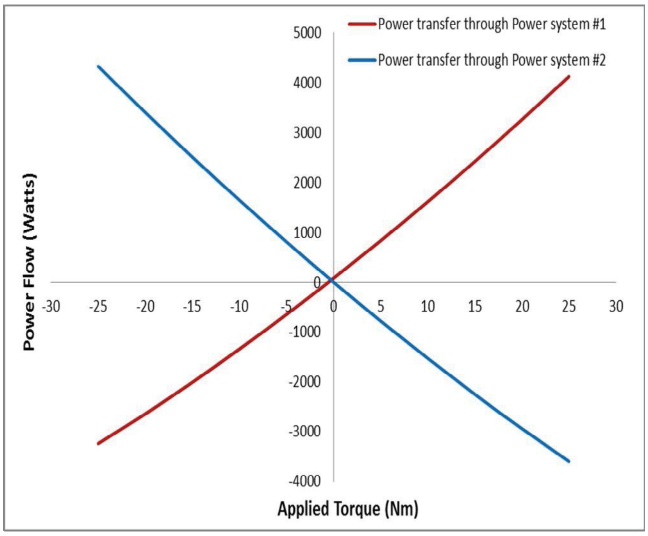


Figure 19. The power transfer in-between synchronous power system networks with the applied torque.

C. Power Flow Control in-between Asynchronous Power Systems

One distinct advantage of a VFT system over that of a conventional PAR is that it can control power flow between two asynchronous power system networks. Unlike a conventional transformer, PAR, or AC transmission line which creates a synchronous connection that can be problematic if frequency variations between systems are common, the VFT can connect both systems without forcing them to operate in synchronism.
For the analysis of power flow control in-between asynchronous power system networks in MATLAB Simulink, the power system#1 and power system#2 are different power systems having different voltages and different frequencies. The power system#1 are kept at 400V (L-L) and 60 Hz whereas power system#2 is kept at 300V (L-L) and 50 Hz. Then this simulated model, as shown in Fig. 2, is used to analyze electric power system using VFT. Under different torque conditions, the power transfer through power system#1 and power system#2 is simulated. The simulated waveforms of stator voltage, rotor voltage, stator current, rotor current, speed and torque are shown in [9].

Power Flow from Power system#1 to Power system#2:- The magnitude and frequency of voltage are kept same for all operating conditions (Fig. 20).

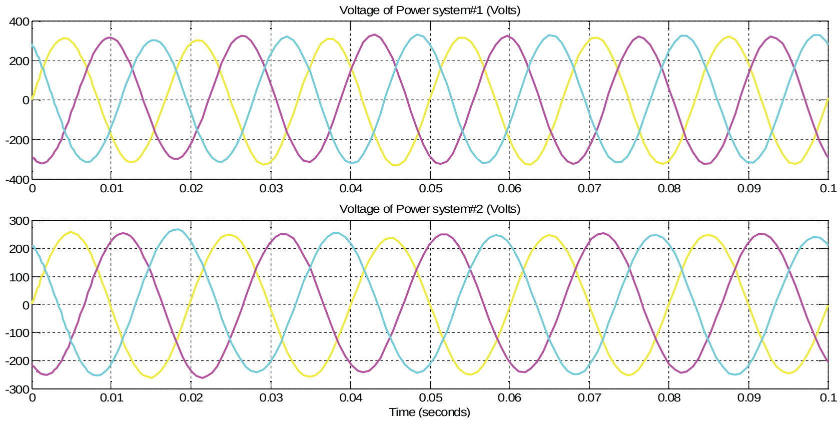


Figure 20. Per phase voltage waveforms of stator and rotor side of VFT

The power transfer through power sytem#1 and power system#2 under different torque condition are shown in Table V.

TABLE V. MATLAB SIMULATION RESULTS FOR IN-BETWEEN ASYNCHRONOUS POWER SYSTEMS

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r (W)
1	0	6.813	214	3.338	36.65
2	5	5.401	1089	3.088	-781.9
3	10	4.635	2010	2.528	-1564
4	15	4.827	2967	3.096	-2304
5	20	5.871	3964	4.518	-3005

It is clear from table V that under zero torque condition the power transfer through the VFT is zero even though there is power transfer through power system#1 and power system#2 i.e. VFT is taking power from both the power systems. When the torque applied is in one direction, then power transmission takes place from power system#1 to power sustem#2. The negative sign represents the power transfer towards the power system#2.

Power Flow from Power system#2 to Power system#1:- When the applied torque is in opposite direction then power transfer direction reverses as shown in Table VI.

It is clear from table VI as the applied torque direction reverses the power transfer direction also reverses i.e. the power transmission takes place from power system#2 to power system#1. The negative sign represents the power flow towards the power system#1.

TABLE VI. MATLAB SIMULATION RESULTS FOR IN-BETWEEN ASYNCHRONOUS POWER SYSTEMS

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r (W)
1	0	6.813	214	3.338	36.65
2	-5	8.587	-624.2	4.937	901
3	-10	10.57	-1416	6.829	1808
4	-15	12.68	-2162	8.882	2763
5	-20	14.91	-2850	11.07	3768

The power transfer through power system#1 and power system#2 with the applied torque achieved is shown in Fig. 21.

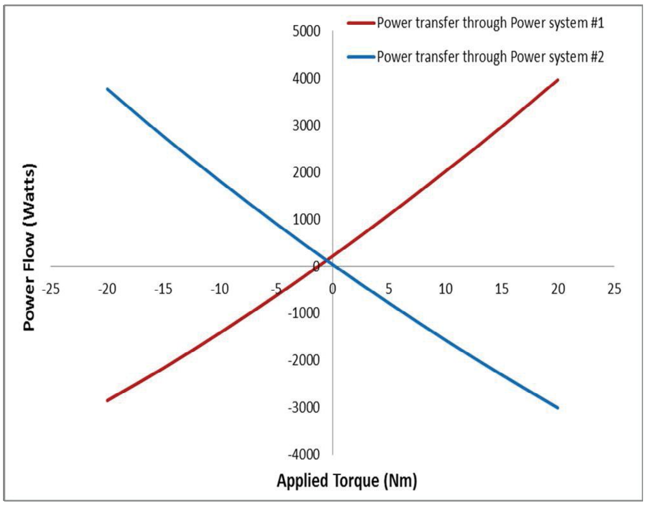


Figure 21. The power transfer in-between asynchronous power system networks with the applied torque

V. CONCLUSIONS

From the simulated result it is evident that power transfer is directly proportional to the external torque applied to the rotor. Moreover, both the magnitude and direction of the power transfer through the connected power system networks are controllable by the torque. Hence, VFT technology is a viable technology for achieving real power transfer control between power system networks. The MATLAB Simulink model developed is successfully used to demonstrate the power transfer through the power system networks. The direction and the magnitude of power transfer control are achieved. The voltage, current, torque and power transfer plots are also obtained. Thus, the VFT concept discussed and its applications are verified by simulation results

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